OPEN ACCESS

University of BRISTOL

Snider, C., Gopsill, J., Jones, S., Shi, L., & Hicks, B. (2015). Understanding Engineering Projects: An Integrated Vehicle Health Management Approach to Engineering Project Monitoring. In C. Weber, S. Husung, M. Cantamessa, G. Cascini, D. Marjanovic, & F. Montagna (Eds.), *Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 3: Organisation and Management, Milan, Italy, 27-30.07.15* (Vol. 3, pp. 65-74). (ICED). https://www.designsociety.org/publication/37737/understanding_engineering_projects_an_integrated_vehicle_health_management_approach_to_engineering_project_monitoring

Peer reviewed version

Link to publication record in Explore Bristol Research

PDF-document

This is the accepted author manuscript (AAM). The final published version (version of record) is available online via The Design Society at https://www.designsociety.org/publication/37737/understanding_engineering_projects_an_integrated_vehicle_health_management_approach_to_engineering_project_monitoring. Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available: http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/

1 INTRODUCTION

As engineering projects have grown with the modern world, a trend towards the large and complex has grown to prominence. Particularly in larger companies and industries, a single project may occupy thousands of engineers and managers, working on tens of thousands of systems and components, generating millions of emails, reports, presentations, and other files. Coupled with this size is the economic value both in individual projects and across markets, and consequent risk of failure to companies involved. At these larger scales the need to effectively deal with the issues faced in engineering projects grows greatly. Considering the complexity (Earl et al. 2005; Al-Ahmad et al. 2009), risk (PMI 2008; Chapman & Ward 1996), and difficulty in knowledge sharing (Dyer & Nobeoka 2000) (amongst other difficulties) inherent in even smaller projects, growing scale becomes an exacerbating factor in project understanding and control (Floricel & Miller 2001; Miller & Lessard 2001). When projects involve many different actors working in many different fields and in many different locations, the challenges associated with understanding the state of the project, managing and mitigating issues, co-ordinating results, and increasing project effectiveness are significant.

This challenge is exacerbated by the technical sophistication of products and increasing international distribution of actors. A wide body of literature within the field of management has begun to address these challenges, such as that on project performance (Egan et al. 2005) and project success and failure (Cooke-Davies 2002; Dvir et al. 1998; Collins & Baccarini 2004), but this understanding has difficulty in application to different contexts and different projects, and struggles to provide trustworthy, evidence-based actionable information upon which managers can act.

This paper begins to address the issues of difficulty in monitoring and understanding projects through the application of a recently developed approach used in machine design – *Integrated Vehicle Health Monitoring (IVHM)* (British Standards 2003; Jennions 2011). Taking a data-driven, bottom-up approach, IVHM generates actionable information automatically, directly from the operation of the machine under analysis. By taking advantage of the principles of this approach, this paper demonstrates the feasibility of such an approach in engineering project management, and its ability to mitigate the context sensitivity found in typical monitoring techniques.

To enable an IVHM approach, it is first necessary to synthesise a list of information categories related to projects that are instrumental in the process and eventual success of the project output. This work derives 75 distinct but inter-dependent project features to be used as targets for analysis (necessary for the application of an IVHM approach), each of which describes or influences overall project performance to varying degrees. These features have not previously been synthesised in an engineering context, and are a primary output of this work. Second, it is necessary to demonstrate that these, likely high-level, categories can be analysed directly from lowest-level data. This is achieved in this paper though analysis of real-life, automatically gathered, low-level engineering data. By synthesising these features, demonstrating their usefulness, and the ability to analyse them, this paper explores the feasibility, and usefulness of the IVHM approach in engineering project management.

2 HIGH LEVEL PROJECT MONITORING AND UNDERSTANDING

A key aim of much research in project management, and that of the IVHM approach in machine design, is the ability to monitor a project (or machine for IVHM) in-progress and provide early indication of its likely performance or output performance. This aim requires understanding of exactly what constitutes good performance or project success; a goal that it has proven problematic to meet but is vital in understanding the benefits of an IVHM-based approach to engineering management.

Within project management, measurement of performance is typically judged through what are termed success *factors* and success *criteria*. *Factors* within literature are those situations within a project that determine whether it will be successful or unsuccessful. As such, they are highly subject to the wide contextual and situational variation that projects themselves will exhibit, leading to a wide variety of factors within literature. As example, (Schmidt et al. 2001) produced 53 risk factors for project success in software ranging from the corporate environment to staffing to technology; (Pinto & Mantel Jr. 1990) present factors relating to failure in three different phases of the project - implementation, perceived value, and client satisfaction; (Chua & Lam 2005) divides success into four discrete categories in knowledge management – technology, culture, content, and project management. *Criteria* within literature are the metrics by which success can be judged, historically taken to be the *iron triangle* in project management – time, cost, and quality (Toor & Ogunlana 2010; Atkinson 1999) – where a successful project will meet specified goals or achieve minimal and maximal values for each. In more recent research, this triangle has been broadened significantly to include elements of satisfaction to stakeholder and end-user, specific benefits, and strategic goals (Lavagnon 2009; Atkinson 1999), taking into account the broader perspectives of success.

While each of these bodies of work give invaluable understanding to aid the management of projects and improve project output and processes, difficulty occurs in applying them to real-life projects in two ways. First, when considering the cross-contextual nature of engineering projects, which vary greatly in terms of size, scope, budget, field, and time criticality; all of which create a variant context in which the projects occur. Consequently, as this variation in context exists, so does the priority assigned to different metrics of assessment and performance and correspondingly the impact of each on the success of the whole. This difficulty has also received attention in literature, and highlights the difference in assessment dependent on perspective (Toor & Ogunlana 2010). The management of a project from a strategic or operational viewpoint (Shenhar et al. 2001) demands differing judgements of success, as does the judgement of success of project or product (Collins & Baccarini 2004; Baccarini 1999), or success as judged by different stakeholders (Toor & Ogunlana 2010). Second, as both success *factors* and *criteria* operate at a high and abstracted level, it is difficult to determine exactly *how* a real project can be measured in terms of any performance measure, how any success factor can be identified on an in-progress basis, or even which factors and criteria are of priority in each project. For example, particularly in large or high complexity projects, it can be difficult to say whether a project is progressing on time, hence requiring bespoke research and development of measurement in each individual project; while contextual variety between projects makes it difficult to determine the cause of any delays that are occurring in each case, what exactly should be measured, and how intervention should take place. Due to the high level nature of success factors and criteria, it is therefore particularly challenging, in not impossible, to relate each to the low level occurrences and situation within each individual projects of distinct context.

In short, as stated by Engwall (2002) and Dvir *et al.* (1998), no project can be understood isolated from context, which significantly impacts progression, success, how interventions may be made, and how it may be improved. Given this contextual requirement, there is a challenge in applying the more generic recommendations and metrics of the management field to individual engineering projects.

3 IVHM AND PROJECT HEALTH

These aforementioned difficulties arising from complexity and context have been addressed in part in the domain of health monitoring. Here there are opportunities to learn from the approaches of *Integrated Vehicle Health Monitoring (IVHM)*, as employed in the aeronautical sector, in which low-level data from the operation of a machine is used to understand its actual state, and then inferred upwards to understand the overall system performance. By adopting this low-to-high approach to project monitoring, there is potential to provide context-appropriate management information.

The premise of IVHM is in the understanding of condition of individual components and sub-systems within a larger whole (see Jennions 2011). Discrete sensing methods are used to detect small, distinct units of information about a single part of a system (such as temperature of a bearing), which are then combined to create a higher level understanding. Through comparison of the change in variables with time against norms, physical principles and performance data, IVHM allows diagnosis of issues, prognosis of future performance or Remaining Useful Life (RUL), and suggests action in the form of decision support. Key within IVHM is the element of integration of simultaneous analyses of multiple components and combined understanding, leading to higher order findings and recommendations. By this approach, IVHM determines the *health* of the project, defined as the combined condition of each individual component or system. The IVHM approach itself can be separated into the seven levels, labelled L1 at the lowest to L7 at the highest. This section describes the IVHM approach as-is, before exploring its usefulness in engineering project management and addressing one key issue – that of gathering appropriate low-level data.

3.1 The IVHM Approach

Starting at the lowest level (L1), IVHM acquires data through instrumentation directly affixed to components, such as temperature, vibration, etc. This is then manipulated to a common or workable form and analysed at L2, following which the data is used to determine the state-of-the-system at L3. This state is a description of performance based on some combination of the instrumented data, chosen as appropriate to the components and system under analysis. For example, a bearing may be instrumented for temperature, vibration, and rotation (data acquisition and manipulation), which together give a description of the bearing wear (system state). In the higher levels of the system, more knowledge must be embedded into the system. L4 takes the description of system state and compares to known principles and typical behaviour, in order to decide whether the system is performing well or poorly. L5 then predicts future performance, typically time-to-failure; L6 generates recommendations to the operators, such as *lubricate the bearing* or *replace within a certain timeframe*, and L7 collates and manipulates all data for best presentation to the operators.

The real strengths of the IVHM approach are in broad applicability to differing systems (with potential for integration into any mechanical system), and strong connection between low-level data and high-level interpretation of system health. For the latter, the automatic understanding generated relating actual performance to overall system health is invaluable. Particularly in larger and complex systems this relationship is non-trivial, where many individual components and sub-systems may influence overall performance. As the IVHM system is able to feed lower level performance data into higher level systems and keeps record with usage, it also allows engineers to quickly understand the complexities of their system in terms of their maintenance, identifying critical and weak systems or components, and in terms of future design iteration and system optimisation.

Through a combination of analyses on each component, leading upwards through each sub-system, IVHM generates a breakdown of performance of all sub-systems within a larger machine. This combinatory understanding gives the definition of machine *health* within IVHM; the combined performance of all related and lower-level sub-systems and components. This definition can be applied at a low level itself to determine component health, or at a whole system level.

3.2 IVHM and Engineering Project Monitoring

There is clear utility in the application of an IVHM approach to engineering project management, particularly in detailed monitoring and understanding of engineering process and systems.

As discussed, a difficulty within the field of project management is cross-relevance and detailed understanding of different and disparate projects in relation to their performance and general "health". Particularly given the heterogeneity of projects in the engineering field this is a major issue for monitoring – even when projects are similar they may go well or poorly in different ways, and this issue is only expounded by differences between projects.

Taking instead an IVHM viewpoint to engineering project monitoring, understanding can be gained and acted upon through low level interpretation of the actual "performance" of the "components" within the project, in this case the engineers, managers, and other actors who perform the project work. This base-to-top approach is counter to the common high-to-low level project management techniques and has scope to provide automatic, and evidence-based understanding of engineering projects through a process that is applicable and effective across engineering contexts.

To begin exploring the applicability of IVHM to an engineering project context, *Project Health* is defined as below. The implication of this and the IVHM definition, is that meaningful learnings of the overall system can be implied from low level and potential quite disparate data, giving a high-level and actionable understanding. This implication is further explored in the following sections.

Project Health: The generalisation of performance of all individual low-level aspects of a project in relation to the project as a whole.

3.3 Engineering Project Structure and Low Level Data

In order to utilise an IVHM approach in engineering project monitoring, low-level data is needed. As in machines, this data is to represent the actual operation of that being studied and should be gathered through direct monitoring of this operation. In an engineering project, the lowest-level consistently operating element is the person completing work, be they an engineer, manager, or other worker. In order to understand how the project is progressing, it is therefore necessary to monitor their work (termed their *activity* in this paper) through any available means; and through monitoring activity a higher-level understanding of the project can be gained.

While the activity of a worker can be monitored in many ways, for the sake of potential automation and lower difficulty in data-gathering this paper proposes the use of *Digital Objects (DO),* those digital files and communications that are produced and iterated throughout all stages and departments of engineering firms. For example, all email, social media communications, CAD files, analysis files (such as FEA, CFD), presentations, spreadsheets, reports, and any other digital entity.

These DOs are all produced by workers during their activity within the project context, and so through their analysis certain information about the project can be inferred. For example, the content of an email, CAD files or presentations can reveal on what people are working; communication and cohesion levels can be determined by shared language and email activity; and morale, motivation, and managerial action can be determined through test-based analysis techniques such as sentiment analysis and linguistic analysis [author ref] completed upon emails or other digital messages. Comparing to the IVHM approach, DOs allow generation of low-level understanding of the actual conditions of a project that influenced their creation, and the activity or operation in which they were created. Should teams be of varying size, varying patterns will appear in communication DOs; should engineers be working at different design stages, the type of DO produced will vary (ie. FEA analysis occurs in a different type of activity and different stage to manufacturing logistics), should a problem be technically difficult, the amount of problem solving emails and communication DOs may increase, and should an issue cause delay in a team, work rates can be inferred from the creation rate of all types of DO. As all DOs are a direct result of the project and activity, they are embedded with elements of the context and project that influenced the manner of their creation.

In this way, DOs act as the source of information for the equivalent of IVHM levels L1 and L2 in engineering project management. By analysing and inferring upwards to the project state, DOs provide the means to describe a project and its context in wider detail, allowing an engineer or manager to generate actionable information to improve the project, its progression, or its performance. This is demonstrated in Section 6 through a real-data example.

4 THE IVHM APPROACH IN ENGINEERING PROJECT MONITORING

While the approach of IVHM in machine monitoring is proven, there is a significant barrier to entry for application in engineering project monitoring. This section addresses this issue, exploring the applicability and form IVHM takes in an engineering project management context.

When working between low-level data and high-level understanding, there is a need to establish a manner in which to directly and reliably relate the two, such that low-level performance can be understood in a high-level health context. In IVHM, this is realised through understanding of physical principles through which the machine operates. For example, the physical principles associated with wear and fatigue are well known and algorithmic, to the extent that wear can be implied from lower level detection of a number of parameters such as temperature and vibration. Basic knowledge of the level of wear and its progression in a machine can be inferred from simple sensor data to determine performance and, for example, the need for component replacement. This is true for many aspects of machine performance - due to extensive knowledge of physical principles, instrumentation and analysis for many machines can be built-in to their development, such that high-level health can be inferred from low-level data. In engineering project monitoring, this pathway does not currently exist to the same extent; there are no consistent "if X, then Y will occur" rules for any given project situation. This lack of principles creates a lack of middle ground between low-level performance and high-level understanding that must be filled for an IVHM approach to be applied.

In analysing DOs to infer the project state, this creates a significant challenge. For example, there is no consistent guidance of whether more communication DOs indicate high or low performance, or whether a high number of DOs relating to a certain sub-system indicate that there is a problem with it, or an issue is likely to appear. To meet this challenge this paper presents 70 *project features* derived from a combination of literature and interview, elements of a project that are important for performance, but are suitably low-level to automatically be related to low-level project data. Project features provide a detailed description of the project, in terms of its overall performance. Through monitoring of these project features, a manager or engineer is able to understand the state of their project in detail and then, using their contextual understanding of the wider project, intervene when necessary to improve performance in the specific areas that are not as expected.

Through formation of these features this paper fulfils one aim of this paper – the synthesis of types of information to generate when applying an IVHM approach in project management. Section 5 presents these features and their development.

4.1 The process of an IVHM approach in engineering project management

The relation between low level data and high-level project health is framed in this work as in Figure 1, following previously presented research (Snider et al. 2014) where a user-in-the-loop approach coupled with algorithmic analysis allows higher levels of information about the project to be inferred. In all projects, depending on how *healthy* it is, it will have different features. These features then influence the workers within the project and the activity that they complete. As DOs are produced during activity and their form will vary depending on the project features at a given point in time, through their analysis it is possible to infer the features of a project. Through further computational analysis or the understanding and interpretation of an informed and knowledgeable manager or engineer, it is then possible for the description of the features of a project to be interpreted as *healthy* or *unhealthy* in each case, allowing processes to be improved.

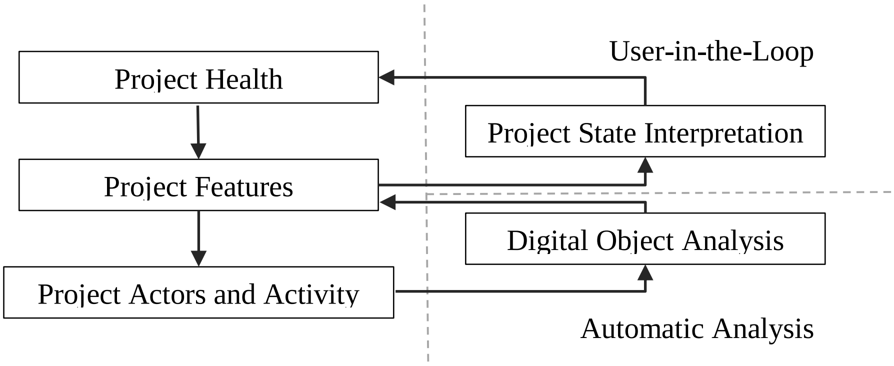


Figure 1: The connection between high-level health and low-level data

A key factor in this approach is the role of the knowledgeable worker in interpreting the health from project features. Due to the contextual heterogeneity of engineering projects, it is impossible to say with reliability and confidence that any state of a project feature will be "good" or "bad" in all cases. The importance and influence of each project feature will vary.

Instead of attempting to make these judgements, the IVHM approach to project monitoring presents the state of the project in terms of its features, and allows a worker who understands the context in detail to make a decision on health and any action that needs to be taken. Because of their inherent knowledge of the project and understanding of how it *should* be, by being presented with detailed information of how it actually is, they can decide whether the project is progressing as expected by any measure they deem important.

5 PROJECT FEATURES

The features of a project are the varying elements that describe or influence its performance and progression. There are clearly numerous features within any project, many of which have been studied and presented in detail in other research. Forming an understanding of all features of engineering projects is therefore a difficult task to achieve, and any list presented should be acknowledged as likely non-exhaustive and subject to change as research continues and projects themselves evolve.

Table 1 presents each feature identified as part of this work, with the features presented generated through two means. Firstly, all features can be found in literature on engineering project performance and project success, and are specifically known to have an influence on overall performance. For example the links between performance and team diversity (McDonough 2000), process dependencies (Cataldo et al. 2008), or change propagation (Eckert et al. 2004). A full reference list is available from the authors but is omitted here due to space constraints. Second, features were confirmed and highlighted through semi-structured interview with industry engineers, focussing on issues that occur within projects and their sources, according to the perspective of the interviewees. Interviewees were seven engineers and project managers from three separate companies, one engineering consultancy, one global metal-packaging firm, and one international engineering software development firm. Participant experience ranged from 66 months to 360 months years (mean 213), and seniority ranged from senior engineer to founder and chief technical officer. All interviews were conducted over a period of one hour, during which interviewees were asked to describe success and issues that they experience within their projects, their sources, and common mitigating practices that they employ. All interviews were audio recorded and transcribed. Transcriptions were analysed inductively initially to determine directly mentioned features, and subsequently deductively in tandem with the features described in literature.

In Table 1, light grey indicates mention in one interview, medium grey indicates mention in between two and five, dark grey indicates more than five. No shading indicates mention in literature but not within interviews. All features are present in literature.

Table 1: Project Features and Definitions

Activity	Duration	The amount of time that is being spent on each activity
	Focus	The focus of the activity that is being performed
	Level	The level of activity that is occuring
	Productivity	The effectiveness of the activity being performed
	Type	The type of activity that is being performed
Comm-unication	Duration	The amount of time spent in communication
	Focus	The focus or specific subjects of communications
	Level	The level of communication that is being transmitted
	Productivity	The effectiveness of communication that is being transmitted
	Type	The type of communication that is being transmitted
Collab-oration	Duration	The amount of time in which collaborative work is being performed
	Focus	The focus of collaborative work being performed
	Level	The level of collaborative work being performed
	Productivity	The effectiveness of collaborative work being performed
	Type	The type of collaborative work being performed
Team	Awareness Level	Awareness of a team of what is happening external to their work
	Cohesion	The shared understanding between actors within a team
	Conflict	Disagreement within a team
	Culture	The relationships between actors within a team
	Experience	The amount, type, and breakdown of relevant experience within a team
	Mode of Working	The type of activity being performed within the team
	Outlook	The perceptions of the team about the work, project, or organisation; including sentiment, uncertainty, motivation, etc.
	Profile	The general characteristics of the team inc. age, specialism, time together, location, etc.
	Roles	The roles of actors within a team, including gatekeepers and champions
	Responsibility	The focus and control of a team in relation to its output goals
	Skills	The categories and technical skills possessed by a team
	Structure	The hierarchy / authority within the team
	Work Habit	The working styles and habits of the team
	Workload	The amount of completed and pending work within a team
Design	Artefact Cost	The 'as-designed' cost of the sum of the components
	Criticality	The importance of the output in terms of consequence of failure to meet requirements
	Definition Level	The detail, clarity, and understanding of purpose of the outputs
	Dependency	The inter-relationship between components in the design outputs
	Knowledge Level	The subject and amount of knowledge of the actor about the design outputs
	Maturity Level	The level of variation required from past outputs to form the current output
	Product Complexity	The sequence and number of functions that the product must perform
	Production Cost	The cost of production in terms of manufacture, assembly, logistics, etc.
	Progress Level	The progress of design of the output as a proportion of functional completion
	Req. Conformance Level	The extent to which the current state of the output satisfies requirements
	Req. Stability Level	The amount of change in number or in value of requirements with time
	Suitability Level	The suitability of the requirements and outputs to solve the initial design problem
	Re-use Level	The level of re-use of past designs
	Robustness	The ability of the design to accommodate changes in requirement, interface, or function
	Similarity Level	The similarity of the outputs to known designs
	Stability Level	The amount that an output varies during its production
	Technical Difficulty	The intellectual difficulty of forming the design
Info	Diffusion	The distribution of information, particularly IP, through the organisation
	Structure	The pathways and ease of information access throughout the organisation
Manage-ment	Engagement	The involvement of managers above the core project actors
	Effectiveness	The improvement and value generated by management of the project
	Buy-in	The support for the project, and alignment with management and organisation goals

Table 2 (cont.): Project Features and Definitions

Process	Compliance	The extent to which the process complies with accepted policies and processes
	Cost	The cost of performing the process for the organisation
	Criticality	The importance of the specific process in terms of failure of completion according to plan and schedule
	Definition Level	The detail, clarity, and understanding of the accepted processes; the schedule and task orders expected
	Dependency	The inter-relation between processes and activities within the project
	Knowledge Level	The subject and amount of knowledge of the actor about the process
	Maturity Level	The level of variation from past processes required in the current process
	Progress Level	The progress of tasks within the project as a proportion of process completion
	Re-use Level	The level of re-use of existing processes
	Robustness	The ability of the process to accommodate change in requirements or design situation
	Sequence Complexity	The sequence, amount of necessary steps and iterations required to perform the process
	Similarity Level	The similarity of the process to follow to known processes
	Stability Level	The amount that the process varies between projects and iterations
	Suitability Level	The suitability of the proces to generate the outputs
	Technical Difficulty	The intellectual effort of following the process
Stake-holder	Buy-in	The support for the project and its current and final direction
	Engagement	The involvement of stakeholders external to the project or organisation
	Relationship	The type of working relationship between the organisation and other stakeholders
	Roles	The roles of the stakeholder, including gatekeepers and champions
	Influence	The level of control over the project, team, or individuals
Resource	Consumption Level	The level of consumption of resources needed for project completion
	Availability Level	The level of resource available for use within the project
	Capability	The feasibility of project completion based on type of resources available
	Churn	The level of change in resource in the project or organisation (inc. staff)

6 REAL-DATA EXAMPLES OF THE IVHM APPROACH

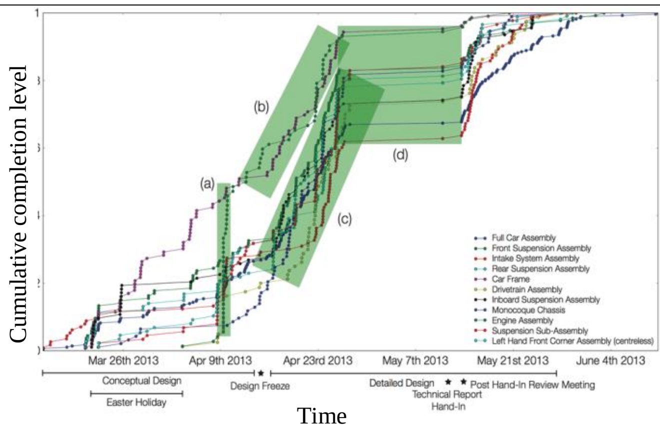
With a detailed list of the information that should be targets for an IVHM approach in engineering project management (as is synthesised in Table 1), the second aim of this paper is to demonstrate the feasibility of generation of this information from low-level engineering data. This section demonstrates this through real-data examples.

From each DO that is analysed in a project, there is potential to inform about multiple project features. Figure 2 shows a number of real-data examples drawn from different data sets, with examples of the project features to which they relate and the implications for project health that they may infer. Data is drawn from a number of previously published works looking specifically at the analysis techniques performed upon them (see Gopsill *et al.* (2014) and Jones *et al.* (2015)). In each example, low-level data is automatically gathered and potential analysis is listed against the features to which it may relate. These examples as presented here are non-exhaustive, with both the analysis methods and relations to features explored from an analysis perspective in other work.

In each case, data is automatically extracted and analysed from DOs within a real-life design process, and presented with explanation of the project features it represents. As such, each demonstrates the feasibility of the overall approach – through a relationship to the project features listed in Section 5, each low-level DO can be used to infer high-level statements about project health. This process demonstrates the feasibility of the second aim of this paper.

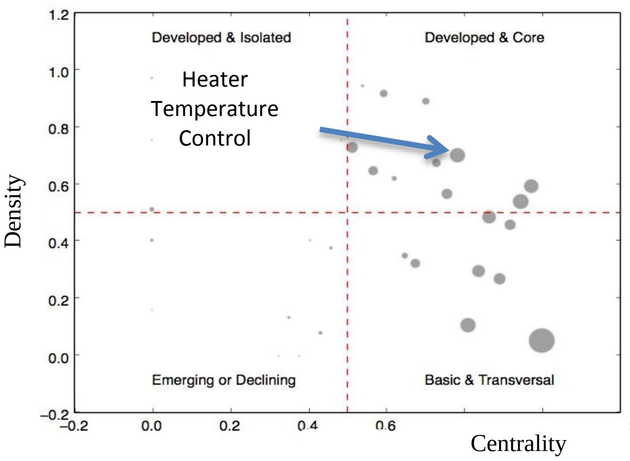
7 DISCUSSION AND CONCLUSION

Due to the variety of contexts within which engineering projects occur, it is difficult to generate consistent methods of monitoring and maintenance, a particularly important task given the high size and complexity common in modern engineering. To attempt to mitigate the need to apply highly abstracted general principles of measuring and causes of failure, this paper has explored the feasibility of applying a different approach – that mirroring the data-driven IVHM to produce a case-by-case understanding of *project health*. This approach has potential for significant benefit in that it relies on evidenced, bottom-up interpretations of real data within a project, generating system level understanding of performance from component level data. While there are issues with its application to a projects rather than machines, primarily the lack of a clear connection between low-level data and high-level understanding, this paper has demonstrated fundamental feasibility.



Data – CAD file creation and modification dates. 1,637 files with 8,508 (Gopsill et al. 2014) gathered from a single 1 year project. Each line represents a sub-system, derived from changes to the parts in contains.

Project Features – *Activity Level*; gradient of curve and consistency between different systems indicates level of activity and work rate. *Time Criticality;* steeper gradients indicate higher criticality for certain systems. *Design Dependency;* lag between sub-systems indicates dependency of work within a system on another.



Data – Topics of emails, determined through co-word analysis. Sample of 10,600 emails from a single 4-year project (Jones et al. 2015). Size of circle indicates dominance of topic in the emails, location indicates importance / connectedness (centrality axis) and maturity / cohesion (density axis) through the company. Data shown is for a single time-slice at month 30.

Project Features – *Team Cohesion;* A highly cohesive team will share terminology, indicated by circles located in developed (high density) locations. *Design Focus;* The subject of each circle indicates the subject of work at a given point in time.

Figure 2: Data examples of project feature and health interpretation

The feasibility of an IVHM approach in engineering project management has been demonstrated through the synthesis of 75 project features, each of with are important in understanding the performance of a project. Through detailing of these features in each given case, a manager is able to produce a comprehensive understanding of their project. Such a list has not previously been generated within the context of the engineering field. This paper has also shown how the state of these features can be generated by low-level data through brief, real-data examples. These examples are explored from an analysis perspective in other work. By this demonstration, this paper has shown the potential for applicability of an IVHM approach in engineering project management, and provided the fundamental types of information that any analysis methods should aim to produce.

An IVHM approach applied to engineering projects has the benefit of being directly embedded in the context of the project under analysis. Instead of applying general principles for success and attempting to work out their relevance in each case, and how they might appear in each different project, an IVHM based approach allows a worker within the context to directly judge their own project based on evidence, determining when and where intervention is needed on a case-by-case basis. Through further development of both the structure of the IVHM approach when applied to engineering project management and the analysis techniques that can be applied to DOs, this paper has demonstrated scope for a comprehensive approach to analysis that is broadly applicable across contexts, and capable of providing the means the relevant, evidence-based intervention and improvement on a case-by-case basis.

ACKNOWLEDGMENTS

This work has been performed as part of the ESPRC Language of Collaborative Manufacture grant based at the University of Bristol. Supporting data can be requested from Dr Chris Snider. Access to supporting data will be granted subject to retrospective consent being requested and granted from the project participants.

REFERENCES

Al-Ahmad, W. et al., 2009. A Taxonomy of an IT Project Failure: Root Causes. *International Management Review*, 5(1), pp.93–104.

Atkinson, R., 1999. Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria. *International Journal of Project Management*, 17(6), pp.337–342.

Baccarini, D., 1999. The logical framework for defining project success. *Project Management Journal*, 30(4), pp.25–32.

British Standards, 2003. *BS ISO 13374-1:2003 Condition monitoring and diagnostics of machines - Data processing, communication and presentation - Part 1: General guidelines*,

Cataldo, M., Herbsleb, J.D. & Carley, K.M., 2008. Socio-Technical Congruence: A Framework for Assessing the Impact of Technical and Work Dependencies on Software Development. In *ESEM'082nd ACM-IEEE international symposium on Empirical software engineering and measurement*. pp. 2–11.

Chapman, C. & Ward, S., 1996. Project risk management: processes, techniques and insights.

Chua, A. & Lam, W., 2005. Why KM projects fail: a multi-case analysis. *Journal of Knowledge Management*, 9(3), pp.6–17.

Collins, A. & Baccarini, D., 2004. Project Success - A Survey. *Journal of Construction Research*, 5(2), pp.211–231.

Cooke-Davies, T., 2002. The "real" success factors on projects. *International Journal of Project Management*, 20(3), pp.185–190.

Dvir, D. et al., 1998. In search of project classification: a non-universal approach to project success factors. *Research Policy*, 27(9), pp.915–935.

Dyer, J.H. & Nobeoka, K., 2000. Creating and Managing a High-Performance Knowledge-Sharing Network: The Toyota Case. *Strategic Management Journal*, 21, pp.345–367.

Earl, C., Eckert, C. & Clarkson, J., 2005. Design Change and Complexity. In *2nd Workshop on Complexity in Design and Engineering*. Glasgow, Scotland.

Eckert, C., Clarkson, P.J. & Zanker, W., 2004. Change and customisation in complex engineering domains. *Research in engineering design*, 15(1), pp.1–21.

Egan, I., Ritchie, J.M. & Gardiner, P.D., 2005. Measuring performance change in the mechanical design process arena. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 219(12), pp.851–863.

Engwall, M., 2002. No project is an island : linking projects to history and context. *Research Policy*, 32(2003), pp.789–808.

Floricel, S. & Miller, R., 2001. Strategizing for anticipated risks and turbulence in large-scale engineering projects. *International Journal of Project Management*, 19(8), pp.445–455.

Gopsill, J.A. et al., 2014. Understanding the Engineering Design Process through the Evolution of Engineering Digital Objects. In *DESIGN 2014: 13th International Design Conference*. Dubrovnik, Croatia.

Jennions, I.K., 2011. *Integrated Vehicle Health Management: Perspectives on an Emerging Field*, Warrendale, PA: SAE International.

Jones, S. et al., 2015. Subject Lines as Sensors: Co-word Analysis of Email to Support the Management of Collaborative Engineering Work. In *ICED'15: International Conference on Engineering Design*. Milan, Italy.

Lavagnon, A.I., 2009. Project success as a topic in project management journals. *Project Management Journal*, 40(4), pp.6–19.

McDonough, E.F., 2000. Investigation of Factors Contributing to the Success of Cross-Functional Teams. *Journal of Product Innovation Management*, 17(3), pp.221–235.

Miller, R. & Lessard, D.R., 2001. *The Strategic Management of Large Engineering Projects: Shaping Institutions, Risks, and Governance*, MIT Press.

Pinto, J.K. & Mantel Jr., S.J., 1990. The causes of project failure. *Engineering Management, IEEE Transactions on*, 37(4), pp.269–276.

PMI, 2008. *A guide to the project management body of knowledge (PMBOK Guide)*, Newton Square, PA: Project Management Institute.

Schmidt, R. et al., 2001. Identifying software project risks: an international Delphi study. *Journal of management information systems*, 17(4), pp.5–36.

Shenhar, A.J. et al., 2001. Project Success: A Multidimensional Strategic Concept. *Long Range Planning*, 34(6), pp.699–725.

Snider, C. et al., 2014. A framework for the development of characteristic signatures of engineering projects. In *DESIGN 2014: 13th International Design Conference*. Dubrovnik, Croatia.

Toor, S.-R. & Ogunlana, S.O., 2010. Beyond the "iron triangle": Stakeholder perception of key performance indicators (KPIs) for large-scale public sector development projects. *International Journal of Project Management*, 28(3), pp.228–236.